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Strangeness-Conserving Hadronic Parity Violation at Low Energies

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Abstract. The parity-violating nucleon-nucleon interaction is the key to understanding the strangeness-conserving hadronic weak interaction at low energies. In this brief talk, I review the past accomplishments in and current status of this subject, and outline a new joint effort between experiment and theory that tries to address the potential problems in the past by focusing on parity violation in few-nucleon systems and using the language of effective field theory.

1. Introduction

Fifty years ago, the seminal paper on parity violation in weak interactions by Lee and Yang, and the subsequent experimental confirmations in β decay of ^{60}Co, muon, and pion is one of the most exciting moments in physics. This discovery fully exemplifies symmetry being a critical character of physical laws; through the study of its conservation or violation, we are able to explore the fundamental interactions and anything beyond our current knowledge boundary. The fruitful achievements can be best summarized in the very successful Standard Model of elementary particle physics, which is based on the $SU(3) \otimes SU(2) \otimes U(1)$ gauge symmetry and provides excellent descriptions of strong, weak, and electromagnetic interactions.

The study of strangeness-conserving ($\Delta S = 0$) hadronic weak interaction, i.e., the weak interaction between two quarks without change of flavor, was started shortly after the discovery of parity violation [1]. However, not until a decade later was the first evidence found by observing a non-zero circular polarization, $P_\gamma = -(6 \pm 1) \times 10^{-6}$, in the γ-decay of ^{181}Ta [2]. The same Leningrad group then performed the first measurement of parity violation in simple nuclear systems using radiative thermal neutron capture by proton, and reported a result $P_\gamma = -(1.30 \pm 0.45) \times 10^{-6}$ [3] which surprised theoretical expectations not only by its being two order of magnitude bigger but also by the sign. This famous Lobashov experiment was eventually redone in the early 80s, and the result $P_\gamma = (1.8 \pm 1.8) \times 10^{-7}$ [4], though with a big error, is now consistent with theory.

Despite lots of efforts being spent in this field, compared to what have been achieved in leptonic, semi-leptonic, and strangeness-changing hadronic weak interactions, our understanding in the $\Delta S = 0$ hadronic sector is still relatively poor. The difficulties are not hard to grasp: Since

Table 1. The five S–P amplitudes, where I denotes the isospin and so do the superscripts in v's and λ's, and the entries in the last column are the corresponding Danilov parameters.

Transition	$I \leftrightarrow I'$	ΔI	n–n	n–p	p–p	Amp.	$E \to 0$
${}^3S_1 \leftrightarrow {}^1P_1$	$0 \leftrightarrow 0$	0		$\surd$		u	λ_t
${}^1S_0 \leftrightarrow {}^3P_0$	$1 \leftrightarrow 1$	0	$\surd$	$\surd$	$\surd$	v^0	λ_s^0
		1	$\surd$		$\surd$	v^1	λ_s^1
		2	$\surd$	$\surd$	$\surd$	v^2	λ_s^2
${}^3S_1 \leftrightarrow {}^3P_1$	$0 \leftrightarrow 1$	1		$\surd$		w	ρ_t

nucleon-nucleon (NN) systems are by far the only viable venue to observe such an interaction, [1] experimentally, one needs high precision to discern the much smaller parity-violating (PV) signals. Theoretically, the non-perturbative character of the quark-gluon dynamics makes a "first-principle" formulation of the PV NN interaction, which one needs to interpret experiments, as yet impossible.

Given the fact that most weak interactions are tested so well, why do we still bother with the $\Delta S = 0$ sector? There are several reasons for it. First: this is the only case where one can study the neutral weak interaction between two quarks—the $\Delta S \neq 0$ sector involves only charged currents. Therefore, we still need this missing piece to make the whole weak interaction theory complete. Second, and maybe more important from the modern perspective: as this interaction comes out as an intricate interplay between the fundamental weak interaction and the nonperturbative QCD, it can, in another way, provide additional information about the low-energy strong dynamics, which is not probed by usual scattering processes. Third, and somewhat related to the previous one: we know, in the $\Delta S = 1$ hadronic weak interaction, the famous $\Delta I = 1/2$ rule—a good example of how strong interaction modifies the fundamental weak interaction. It would be valuable to have some complementarity in the $\Delta S = 0$ sector. Last but not least: several PV experiments via semi-leptonic processes are in fact complicated by hadronic contributions. Two examples which are particularly of interest to this meeting are i) the PV electron proton or deuteron scattering which aims to explore the strangeness content of a nucleon and ii) the atomic PV and Qweak experiments which try to determine how the Weinberg angle $\sin^2\theta_W$ evolves with Q^2 (~ 0 for the former and $\sim 10^{-2}\,\mathrm{GeV}^2$ for the latter). [2] For better interpretation of these experiments, the hadronic contributions appearing in terms of axial form factor or anapole moment should be properly taken into account.

This short review is organized as following: The past accomplishments in and the current status of the PV NN interaction are first reviewed in section 2. A new joint effort between experiment and theory that tries to address the potential problems in the past by focusing on parity violation in few-nucleon systems and using the language of effective field theory (EFT) is then outlined in section 3, followed by a brief summary in section 4.

2. The Old Paradigm

At low energies, two nucleon scattering mainly goes through the S-wave channel, therefore, the PV NN interaction, V^{PV}, then induces a small P-wave admixture. It is first pointed out by Danilov [7, 8, 9] that, at low energies, V^{PV} can be fully characterized by five such S–P scattering amplitudes as tabularized in table 1. Their zero-energy limits, the so-called Danilov parameters, are the quantities to be determined phenomenologically. As these two-body PV experiments were beyond experimental capability in those times, most measurements were performed in heavier

[1] There are theoretical explorations of parity violation in processes such as pion photo- and electro-productions (Refs. [5, 6]). However, they have not been experimentally realized.

[2] For these topics, please refer to contributions by D. Armstrong, K. Paschke, and P. Souder in the same volume.

nuclei. For this purpose, Desplanques and Missimer [10] extend this idea, by applying the Bethe-Goldstone equation, to many-body systems. This PV potential in terms of the S–P amplitudes takes the form

$$\begin{aligned} V^{\rm PV}_{S-P}(\boldsymbol{r}) &= \frac{4\,\pi}{m_N}\bigg\{\left[v^0\,\frac{1}{4}\,(3+\tau_\cdot)+v^1\,\tau^z_+ + v^2\,\tau^{zz}\right]\boldsymbol{\sigma}_-\cdot\{-i\,\boldsymbol{\nabla}\,,\,\delta(\boldsymbol{r})\} \\ &\quad + u\,\frac{1}{4}\,(1-\tau_\cdot)\,\boldsymbol{\sigma}_-\cdot\{-i\,\boldsymbol{\nabla}\,,\,\delta(\boldsymbol{r})\} + w\,\tau^z_-\,\boldsymbol{\sigma}_+\cdot\{-i\,\boldsymbol{\nabla}\,,\,\delta(\boldsymbol{r})\}\bigg\}\,, \end{aligned} \tag{1}$$

where m_N is the nucleon mass, $\tau_\cdot \equiv \boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2$, $\tau^z_\pm \equiv (\tau^z_1 \pm \tau^z_2)/2$, $\tau^z_\times \equiv i\,(\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2)^z/2$, and $\tau^{zz} \equiv (3\,\tau^z_1\,\tau^z_2 - \boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)\,/(2\,\sqrt{6})$ are the isospin operators; $\boldsymbol{\sigma}_\pm \equiv \boldsymbol{\sigma}_1 \pm \boldsymbol{\sigma}_2$ and $\boldsymbol{\sigma}_\times \equiv i\,\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2$ are the spin operators. [3] Though a lot of pre-80s data are analyzed in this framework [10, 11, 12], no detailed consistency check has been performed along this line; and this framework has almost been forgotten after 80s, partly because the meson-exchange picture gets more popularity.

The formulations of $V^{\rm PV}$ in terms of meson exchange, which can be dated back to the works by Blin-Stoyle [13, 14] and Barton [15], are in fact not much younger than the S–P amplitude framework. Using the Barton's theorem—which forbids any PV coupling between a nucleon and a neutral pseudoscalar meson by CP invariance—and considering mesons below GeV scale, one is left with $\pi^\pm$, ρ, and ω mesons. The resulting potential has seven PV meson-nucleon couplings, h^i_x's (x denotes the type of meson and i the isospin) and takes the form

$$V^{\rm PV}_{\rm OME}(\boldsymbol{r}) = V^{\rm PV}_{\rho,\omega}(\boldsymbol{r}) + V^{\rm PV}_{\pi}(\boldsymbol{r})\,, \tag{2}$$

$$\begin{aligned} V^{\rm PV}_{\rho,\omega}(\boldsymbol{r}) &= \frac{-1}{m_N}\Big\{g_\rho\,\left[h^0_\rho\,\tau_\cdot + h^1_\rho\,\tau^z_+ + h^2_\rho\,\tau^{zz}\right]\,(\boldsymbol{\sigma}_-\cdot\boldsymbol{u}_{\rho+}(\boldsymbol{r}) + i\,(1+\chi_\rho)\,\boldsymbol{\sigma}_\times\cdot\boldsymbol{u}_{\rho-}(\boldsymbol{r})) \\ &\quad + g_\omega\,\left[h^0_\omega + h^1_\omega\,\tau^z_+\right]\,(\boldsymbol{\sigma}_-\cdot\boldsymbol{u}_{\omega+}(\boldsymbol{r}) + i\,(1+\chi_\omega)\,\boldsymbol{\sigma}_\times\cdot\boldsymbol{u}_{\omega-}(\boldsymbol{r})) \\ &\quad - g_\rho\,h^1_\rho\,\tau^z_-\,\boldsymbol{\sigma}_+\cdot\boldsymbol{u}_{\rho+}(\boldsymbol{r}) + g_\omega\,h^1_\omega\,\tau^z_-\,\boldsymbol{\sigma}_+\cdot\boldsymbol{u}_{\omega+}(\boldsymbol{r}) \\ &\quad + g_\rho\,h^{1'}_\rho\,\tau^z_\times\,\boldsymbol{\sigma}_+\cdot\boldsymbol{u}_{\rho-}(\boldsymbol{r}) - \Big\}\,, \end{aligned} \tag{3}$$

$$V^{\rm PV}_{\pi^\pm}(\boldsymbol{r}) = \frac{1}{\sqrt{2}\,m_N}\,g_\pi\,h^1_\pi\,\tau^z_\times\,\boldsymbol{\sigma}_+\cdot\boldsymbol{u}_{\pi-}(\boldsymbol{r})\,, \tag{4}$$

where g_x's denote the parity-conserving (PC) x-meson-nucleon couplings; χ_ω and χ_ρ are the isoscalar and isovector strong tensor couplings, respectively; the spatial operator $\boldsymbol{u}_{x-(+)}(\boldsymbol{r})$ is defined as the (anti-) commutator of $-i\,\boldsymbol{\nabla}$ with the Yukawa function $f_x(r)$

$$\boldsymbol{u}_{x\pm}(\boldsymbol{r}) = [-i\,\boldsymbol{\nabla}\,,\,f_x(r)]_\pm \equiv \left[-i\,\boldsymbol{\nabla}\,,\,\frac{{\rm e}^{-m_x\,r}}{4\,\pi\,r}\right]_\pm\,. \tag{5}$$

The attractiveness of this meson-exchange picture is apparent: not only there are not much more undetermined parameters, but also it provides a transparent gateway between phenomenology and the underlying theory—one can actually perform hadronic calculations of these couplings and compare with fits from experiments. This above form then becomes the standard in this field after Desplanques, Donoghue, and Holstein (DDH) give their prediction for these meson-nucleon coupling constants, based on a quark model calculation [16].

Several hadronic calculations of these coupling constants are compared in table 2. The "best" guess values by DDH are pretty consistent with two other quark model calculations (DZ [17] and FCDH [18]). However, as stressed by DDH, their best values have to be understood in the context

[3] In the actual analyses by Desplanques and Missimer, the one-pion-exchange contribution is added separately in order to better present the long-range part of the w-type amplitude, i.e., the ${}^3S_1$–${}^3P_1$ transition.

Table 2. Hadronic predictions for the seven PV meson-nucleon coupling constants (see text for explanation of abbreviations and references).

	Quark Model							χ-Soliton	QCD SR		LQCD
$\times 10^7$	DDH Range			Best	DZ	FCDH		KM	HHK	Lobov	BS
h_π^1	0.0	$\leftrightarrow$	11.4	4.6	1.1	2.7		0.2	3.0	3.4	proposed
h_ρ^0	-30.8	$\leftrightarrow$	11.4	-11.4	-8.4	-3.8		-3.7			
h_ρ^1	-0.4	$\leftrightarrow$	0.0	-0.2	0.4	-0.4		-0.1			
h_ρ^2	-11.0	$\leftrightarrow$	-7.6	-9.5	-6.8	-6.8		-3.3			
h_ω^0	-10.3	$\leftrightarrow$	5.7	-1.9	-3.8	-4.9		-6.2			
h_ω^1	-1.9	$\leftrightarrow$	-0.8	-1.1	-2.3	-2.3		-1.0			
$h_\rho^{1'}$				0.0				-2.2			

of the very modest "allowed" ranges (the second column of table 2), which are a rough estimate of potentially huge theoretical uncertainties. Thus, for example, despite the DDH best value for h_π^1 differs by an order of magnitude from the prediction of another quark model, the chiral soliton model (KM [19, 20]), these two results are still well within the allowed range. For the most interested quantity h_π^1, there are two consistent QCD Sum Rule calculations (HHK [21, 22] and Lobov [23]), which seem to favor DDH's result. But, it is still premature to make any judgment at this stage, and will be very interesting to see how the proposed lattice QCD effort (BS [24]), if ever realized, can provide us a more definitive answer.

On the other hand, what are the experimental constraints on these PV coupling constants? Although quite a few data has been accumulated during the past years, not all of them have small errors to be constrictive. Using the several precise data available to date, it is fair to say that experiment and theory have not reached consistency. Two majors puzzles are illustrated in FIG. 1 of Ref. [25] and FIG. 8 of Ref. [26]. In the former figure, a less ambitious two dimensional fit to some linear combinations of these seven couplings is plotted. The constraints from the anapole moments of ^{133}Cs and ^{205}Tl clearly contradict with each other. Although the ^{133}Cs result probes the similar linear combination of PV couplings as ones of the $\vec{p}\alpha$ and ^{19}F experiments, it favors larger values. If one discards anapole constraints, the nuclear PV data do have an agreed region, where the isoscalar coupling combination agrees with the DDH best guess, but the isovector coupling combination, mostly determined by h_π^1 (it is denoted as f_π there), favors a much smaller value than the DDH best guess—however, still in the allowed range. The latter tight constraint, set by the ^{18}F data, is thought to be pretty robust as the experiments are repeated by five different groups and the nuclear matrix elements are calibrated well from analogous β decay data. The second puzzle comes from the $\vec{p}p$ asymmetry measurements performed at 13.6, 45, and 221 MeV. In the $V_{\rm OME}^{\rm PV}$ framework, these asymmetries only depend on two linear combinations of the PV couplings: $h_\rho = h_\rho^0 + h_\rho^1 + h_\rho^2/\sqrt{6}$ and $h_\omega = h_\omega^0 + h_\omega^1$; therefore, h_ρ and h_ω should be uniquely determined by these experiments. As one can see from the latter figure, the fitted value of $h_\rho \sim -20$ is consistent with the DDH best guess, but the one of $h_\omega \sim 5$ is only marginally consistent with the very modest DDH reasonable range and is in large discrepancy with other theoretical predictions.

3. The New Direction

There can be many reasons for this unsettling situation: First, the experiments might have their own problems. Second, as most data are obtained in nuclear systems of medium to heavy mass, the reliability of many-body calculations can be questioned. Third, one may wonder if the meson-exchange model is really adequate.

In the last decade, we have seen quite some accomplishments in applying the EFT

technique to the construction of parity-conserving two- and few-nucleon forces. Though there is still gap to catch up with the success of modern, high-quality, phenomenological potentials, this framework has the advantages of being completely general, model-independent, and systematically improvable. Therefore, in order to avoid the potential problems associated with the meson-exchange picture, Zhu et al. recently applied the similar EFT technique and proposed a re-formulation of $V^{\rm PV}$ to the order of Q (Q is the momentum scale) [27].

At this order, the PV potential, $V^{\rm PV}_{\rm EFT}$, contains three components: [4]

$$V^{\rm PV}_{\rm EFT}(\boldsymbol{r}) = V^{\rm PV}_{1,\rm SR}(\boldsymbol{r}) + V^{\rm PV}_{-1,\rm LR}(\boldsymbol{r}) + V^{\rm PV}_{1,\rm MR}(\boldsymbol{r})\,. \tag{6}$$

1) The short-range (SR) part: This consists of the four-fermion contact operators which meet all the symmetry requirements. It is expressed, with 10 undetermined low-energy constants (LECs) C's and $\widetilde{C}$'s, [5] as

$$\begin{aligned} V^{\rm PV}_{1,\rm SR}(\boldsymbol{r}) \;=\; & \frac{2}{\Lambda_\chi^3}\Big\{ \left[C_1 + (C_2+C_4)\,\tau_+^z + C_3\,\tau. + C_5\,\tau^{zz}\right]\,\boldsymbol{\sigma}_-\cdot\boldsymbol{y}_{x-}(\boldsymbol{r}) \\ & + \left[\widetilde{C}_1 + (\widetilde{C}_2+\widetilde{C}_4)\,\tau_+^z + \widetilde{C}_3\,\tau. + \widetilde{C}_5\,\tau^{zz}\right]\,\boldsymbol{\sigma}_\times\cdot\boldsymbol{y}_{x-}(\boldsymbol{r}) \\ & + (C_2 - C_4)\,\tau_-^z\,\boldsymbol{\sigma}_+\cdot\boldsymbol{y}_{x+}(\boldsymbol{r}) + \widetilde{C}_6\,\tau_\times^z\,\boldsymbol{\sigma}_+\cdot\boldsymbol{y}_{x-}(\boldsymbol{r})\Big\}\,, \end{aligned} \tag{7}$$

where Λ_χ is the scale of chiral symmetry breaking and related to the pion decay constant F_π by $\Lambda_\chi = 4\,\pi\,F_\pi \approx 1.161\,\mathrm{GeV}$. The spatial operator $\boldsymbol{y}_{m\pm}(\boldsymbol{r})$ have the properties that i) it is strongly peaked at $r=0$ with a range about $1/m_x$, and ii) it approaches $\delta(\boldsymbol{r})$ in the zero range (ZR) limit (i.e., $m_x\to\infty$). A convenient choice, to mimic the meson-exchange picture, is

$$\boldsymbol{y}_{x\pm}(\boldsymbol{r}) = m_x^2\,\boldsymbol{u}_{x\pm}(\boldsymbol{r}) \to [-i\,\boldsymbol{\nabla}\,,\,\delta(r)/r^2]_\pm\,. \tag{8}$$

When one sets $m_x = m_{\rho,\omega}$ and assume the following relations between C- and $\widetilde{C}$-type LECs

$$\frac{\widetilde{C}_1}{C_1} = \frac{\widetilde{C}_2}{C_2} \;=\; 1+\chi_\omega\,, \tag{9}$$

$$\frac{\widetilde{C}_3}{C_3} = \frac{\widetilde{C}_4}{C_4} = \frac{\widetilde{C}_5}{C_5} \;=\; 1+\chi_\rho\,, \tag{10}$$

then $V^{\rm PV}_{1,\rm SR}(\boldsymbol{r})$ is tantamount to the short-range sectors of $V^{\rm PV}_{\rm OME}(\boldsymbol{r})$: the ones corresponding the ρ- and ω-exchanges $V^{\rm PV}_{\rho,\omega}(\boldsymbol{r})$. Also, in the ZR limit, one can see that $\boldsymbol{y}_{\infty-}(\boldsymbol{r})$ and $\boldsymbol{y}_{\infty+}(\boldsymbol{r})$ have the same matrix element. Therefore, $V^{\rm PV}_{1,\rm SR}(\boldsymbol{r})$ can be mapped to $V^{\rm PV}_{S-P}(\boldsymbol{r})$ so that the 10 LECs at the superficial level can be reduced to 5, which corresponds to the number of the physical S–P amplitudes.

2) The long-range (LR) part: This is the leading order term in EFT (subscripted as "-1") and corresponds to the familiar PV one-pion-exchange potential,

$$V^{\rm PV}_{-1,\rm LR}(\boldsymbol{r}) = V^{\rm PV}_{\pi^\pm}(\boldsymbol{r})\,, \tag{11}$$

which depends on h^1_π.

[4] An additional higher-order long-range term $V^{\rm PV}_{1,\rm LR}$ in Ref. [27] is omitted here, since it is shown to be redundant [28].

[5] The notations here are of Ref. [29].

3) The medium-range (MR) part: This is resulted from two-pion-exchange (TPE) contributions with one of the four pion-nucleon couplings being PV (therefore, also depends on h_π^1). It takes the form

$$
\begin{aligned}
V_{1,\mathrm{MR}}^{\mathrm{PV}}(\boldsymbol{r}) &= \frac{2}{\Lambda_\chi^3}\Bigg\{-4\sqrt{2}\,\pi\,g_A^3\,h_\pi^1\,\boldsymbol{\sigma}_\times\cdot\boldsymbol{y}_{2\pi}^L(\boldsymbol{r}) \\
&\quad +3\sqrt{2}\,\pi\,g_A^3\,h_\pi^1\,\tau_\times^z\,\boldsymbol{\sigma}_+\cdot\left[\left(1-\frac{1}{3\,g_A^2}\right)\boldsymbol{y}_{2\pi}^L(\boldsymbol{r})-\frac{1}{3}\,\boldsymbol{y}_{2\pi}^H(\boldsymbol{r})\right]\Bigg\}, \qquad (12)\\
\boldsymbol{y}_{2\pi}^L(\boldsymbol{r}) &= \left[-i\,\boldsymbol{\nabla}\,,\,\mathrm{F.T.}\left(\frac{\sqrt{4\,m_\pi^2+\boldsymbol{q}^2}}{|\boldsymbol{q}|}\,\ln\left(\frac{\sqrt{4\,m_\pi^2+\boldsymbol{q}^2}+|\boldsymbol{q}|}{2\,m_\pi}\right)\right)\right], \qquad (13)\\
\boldsymbol{y}_{2\pi}^H(\boldsymbol{r}) &= \left[-i\,\boldsymbol{\nabla}\,,\,\mathrm{F.T.}\left(\frac{4\,m_\pi^2}{|\boldsymbol{q}|\,\sqrt{4\,m_\pi^2+\boldsymbol{q}^2}}\,\ln\left(\frac{\sqrt{4\,m_\pi^2+\boldsymbol{q}^2}+|\boldsymbol{q}|}{2\,m_\pi}\right)\right)\right], \qquad (14)
\end{aligned}
$$

where "F.T." denotes a Fourier transform from q- to r-space. [6] Note that both the MR and SR interactions appear at the same EFT order (next-to-next-to-leading, subscripted as "1"), and their expressions should be understood in the context of the specific regularization scheme. The MR interaction as given by Zhu et al. only contains the non-analytic part of TPE; all the analytic part has been effectively included in the SR interaction [27].

Overall, this new formulation contains 6 (5 LECs plus h_π^1) undetermined parameters. Though this number seems comparable to 7 in the OME framework, one has to note that this EFT formulation is only to $O(Q)$; therefore, one should be very careful when trying to analyse not-so-low-energy processes (e.g., $\vec{p}p$ scattering at 221 MeV is obviously out of scope). On the other hand, if one further limits the momentum scale under the pion mass, i.e., $Q \ll m_\pi \cong 140\,\mathrm{MeV}$, which corresponds to an energy scale of $E \ll 10\,\mathrm{MeV}$, then the pion degrees of freedom can be integrated out and this leads to a pionless theory where only 5 LECs are needed. Although this pionless framework requires less parameters (by one), the most interested PV constant h_π^1 becomes obscure since it is implicitly included in LECs.

For determining these six parameters, a search program has also been sketched out in Ref. [27]. The basic idea is to explore as many low-energy observables in few-nucleon systems as possible. With the advance of experimental apparatus and techniques, PV experiments in few nucleon systems with 10% precision become feasible nowadays. Furthermore, modern few-body calculations are also sophisticated enough to allow reliable interpretations of these experiments. Combining the model-independent PV NN interaction based on EFT, we should be able to properly address the above-mentioned problems that possibly undermine a consistent picture of nuclear parity violation.

Both experimental and theoretical efforts in this broad program are summarized, but not exhaustively, in table 3.

On the experimental side, there are two existing data points, the low-energy $\vec{p}p$ scattering (the 13.6 and 45 MeV experiments measure virtually the same parameter) and $\vec{p}\alpha$ scattering. There are two ongoing experiments: the asymmetry measurement in radiative polarized neutron capture on proton at the Los Alamos Neutron Science Center (LANSCE) and the thermal neutron spin rotation measurement in liquid helium at the National Institute of Standard and Technology (NIST). The Fundamental Neutron Physics Beamline (FNPB) program, which is going to take advantage of the high-intensity, pulsed neutron beam from the just-completed Spallation Neutron Source (SNS), will consider other neutron-induced processes. Overall, it looks very promising that enough data will be taken in the near future.

[6] Some mistakes in Eq. (121) of Ref. [27] have been fixed in order to produce Eqs. (13, 14); see Refs. [30, 29].

Table 3. The nuclear PV search program in few-nucleon systems (non-exhaustive).

Observables	Theory	Experiment ($\times 10^7$)
$A_L^{\vec{p}p}(13.6\,\mathrm{MeV})$	$-0.45\, m_N \lambda_s^{pp}$ [a]	-0.93 ± 0.21 (Bonn) [31]
$A_L^{\vec{p}p}(45\,\mathrm{MeV})$	$-0.78\, m_N \lambda_s^{pp}$ [a]	-1.57 ± 0.23 (SIN) [32]
$\frac{d}{dz}\,\phi_n^{\vec{n}p}(\mathrm{th.})$	$[2.50\,\lambda_s^{np} - 0.57\,\lambda_t + 1.41\,\rho_t]\ m_N + 0.29\,\widetilde{C}_6^{\pi}$ [a]	SNS
$P_\gamma^{np}(\mathrm{th.})$	$[-0.16\,\lambda_s^{np} + 0.67\,\lambda_t]\ m_N$ [a]	(1.8 ± 1.8) [4], SNS?
$A_L^{\vec{\gamma}d}(1.32\,\mathrm{keV})$	Same as above [a]	HIGS? IASA? Spring-8?
$A_\gamma^{\vec{n}p}(\mathrm{th.})$	$-0.09\, m_N \rho_t - 0.27\,\widetilde{C}_6^{\pi}$ [a]	(0.6 ± 2.1) [33], LANSCE [c]
$\frac{d}{dz}\,\phi_n^{\vec{n}d}(\mathrm{th.})$	To be done	SNS?
$A_\gamma^{\vec{n}d}(\mathrm{th.})$	$[0.59\,\lambda_s^{nn} + 0.51\,\lambda_s^{np} + 1.18\,\lambda_t + 1.42\,\rho_t]\ m_N$ [b]	(42 ± 38) [34], SNS?
$A_L^{\vec{p}\alpha}(46\,\mathrm{MeV})$	$[-0.48\,\lambda_s^{pp} - 0.24\,\lambda_s^{np} - 0.54\,\lambda_t - 1.07\,\rho_t]\ m_N$ [b]	-3.3 ± 0.9 (SIN) [35]
$\frac{d}{dz}\,\phi_n^{\vec{n}\alpha}(\mathrm{th.})$	$[1.2\,\lambda_s^{nn} + 0.6\,\lambda_s^{np} + 1.34\,\lambda_t - 2.68\,\rho_t]\ m_N$ [b]	(8 ± 14) [36], NIST [c]

a) Results taken from Ref. [29].

b) Results taken from Ref. [27]. These calculations have to be improved, and also be checked with calculations using the pionful theory since it is questionable if the pionless framework can apply to these cases (See Ref. [29] for some remarks).

c) With plans continuing at SNS.

On the theoretical side, the re-analysis of these PV observables is also under way [29]. This is done in the so-called "hybrid" EFT fashion, which marries the general PV potential derived from the EFT consideration and the start-of-the-art nuclear wave functions obtained from phenomenological model calculations. The 5 independent LECs are completely mapped to the dimensionless Danilov parameters: $m_N \times (\lambda_s^{pp},\, \lambda_s^{nn},\, \lambda_s^{np},\, \lambda_t,\, \rho_t)$ with the long-range one-pion-exchange contribution, characterized by $\widetilde{C}_6^{\pi} \propto h_\pi^1$, being singled out from the ${}^3S_1$–${}^3P_1$ amplitude. [7] The observables in two-body systems have been analyzed with the results given in the table 3. The observables in few-body systems should be analyzed in the same way with updated calculations. These results will be valuable for prioritizing the future measurements.

4. Summary

The study of strangeness-conserving hadronic weak interaction is a challenging task both experimentally and theoretically. Although the efforts in the past fifty years have not been able to provide us a consistent overall picture, the precious lessons learned however motivate a new and promising direction. This new research program consists of three important ingredients: (1) the high-precision measurements of nuclear parity-violation in few-nucleons systems, (2) the reliable few-body calculations using the state-of-the-art techniques to interpret the experiments, and (3) the general, model-independent formulation of the parity-violating nucleon-nucleon interaction, which in combination aim to address the potential problems in the past. The Fundamental Neutron Physics Beamline program at the Spallation Neutron Source is going to trigger a new renaissance for this research, and with intensive joint efforts between experiment and theory, one hopes not only to reach a consistent picture of hadronic weak interaction but also to provide important, additional input for the study of the nonperturbative dynamics of strong interaction.

[7] In this sense, this new framework is a revival of the S–P analysis proposed by Danilov, Desplanques and Missimer (also see footnote 3).

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